Field demonstrations of active laser ranging with sub-mm precision

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ABSTRACT

Precision ranging between planets will provide valuable information for scientific studies of the solar system and fundamental physics. Current passive ranging techniques using retro-reflectors are limited to the Earth-Moon distance due to $1/R^4$ losses. We report on a laboratory realization and field implementation of active laser ranging in real-time with two terminals, emulating interplanetary distances. Sub-millimeter accuracy is demonstrated.

Key Words: precision laser ranging, laser ranging, laser communications

1. INTRODUCTION

Interplanetary laser ranging will enable advances in the study of fundamental physics and solar system dynamics. Precision ranging will enable tests of gravity which may shed light on the apparent acceleration of the expansion of the universe, the possible existence of extra dimensions, and the reconciliation of quantum mechanics with gravity.[1-4] Other applications include determination of the Shapiro time delay due to solar gravity (from measurement of the Earth-Mars distance near solar conjunction) and a test of the equivalence principle in the Earth-Mar-Sun-Jupiter system.[5,6]

Over the last half century, significant progress has been made on passive laser ranging using retro-reflectors; with state-of-the-art technology, passive laser ranging can be stretched up to the distance of the Moon,[7] limited by laser signal decay proportional to $1/R^4$ over a distance of R. One way to extend laser ranging out to interplanetary distances is to use active laser ranging with two asynchronous transponders, similar to bi-directional free space laser communications.[8,9] The reduced attenuation scaling of $1/R^2$ in the active laser ranging system makes laser ranging over interplanetary distances possible.[10] In 2005, a non-real-time laser ranging demonstration using two transponders was demonstrated between the Mercury Laser Altimeter on board the MESSENGER spacecraft and the Earth over a distance of 24×10^6 km (0.16AU).[11] The transmitted and received pulse times were linked via the spacecraft clock, which was periodically synchronized to coordinated universal time (UTC) and was stable to approximately one part per billion. The times of the paired observations were used to solve for a common range and clock offset in a quadratic model with RMS precision ±0.2m, and a deviation from the radiometric ephemeris of less than 52m.[11]

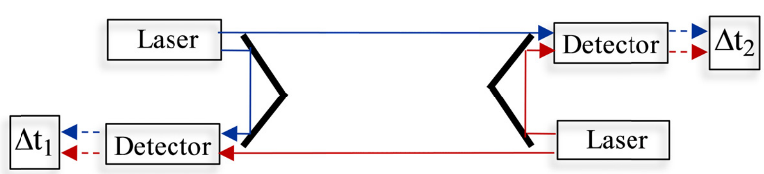


Figure 1. Architecture for paired one-way laser ranging with local references.

In order to overcome the limitations to ranging accuracy from jitters and delay drifts within the transponders, an architecture was proposed based on asynchronous paired one-way ranging with local references.[12] The scheme is shown in Fig. 1, where each terminal can transmit and receive laser pulses. A portion of the transmitted light is directed, via a reference path, to the local detector. This allows for compensation of any jitter in the timing of the emitted laser pulse. The same detector is used to measure the time of the received pulses emitted from the remote terminal. This approach removes any change in the delay caused by the detector or its electronics. The time tags associated with all of the emitted and received pulses from the terminals are used to form the range estimate. This scheme was implemented in a tabletop setup with two terminals, using an optical path with variable length to emulate range variation.[12] Only one laser and one time tag device were used for the two terminals. The critical issue of time synchronization between the two terminals was bypassed via a common trigger/clock for the two channels of the time tag device. This system relies on a single clock for recording the arrival times of the local reference pulses and the remotely launched pulses on the two terminals.

In a practical implementation over planetary ranges (e.g. one terminal on Earth and the other on Mars) a common trigger/clock is not feasible and a clock synchronization method needs to be devised. Below, we describe the development of a synchronization scheme for active laser raging, and successful implementation of the real-time laser ranging system with two asynchronous terminals 10s of meters apart.

2. APPROACH

Fig. 2 is a schematic of the timing diagram of two terminals for asynchronous (paired one-way) ranging. Pulses are transmitted from each terminal to the other independently. An instantaneous range R between the two terminals is evaluated from

$$R=[t_3(j)-t_0(i)+t_2(i)-t_1(j)]c/2 \qquad (1)$$

where c is the speed of light, $t_0(i)$ refers to the time of the ith pulse launched and received by Detector A at the Earth terminal, $t_3(j)$ represents the arrival time of the jth pulse at Detector A of the Earth terminal launched from the Mars terminal, $t_1(j)$ stands for the time of the jth pulse arriving at the Mars Detector B launched from the Mars terminal, and $t_2(i)$ the arrival time of the ith pulse at Mars terminal Detector B launched from the Earth terminal. Since the range is computed from differences in recorded times, transmitter jitters and detector delays are cancelled out.

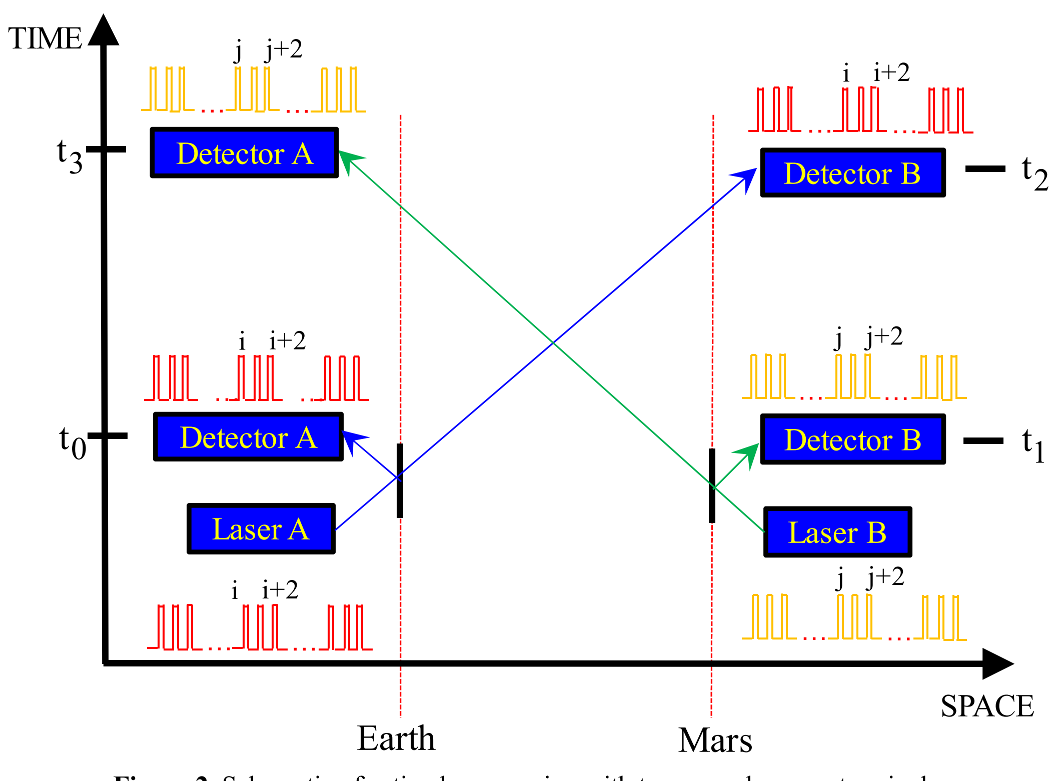


Figure 2. Schematic of active laser ranging with two asynchronous terminals.

To use Equation (1) for the range estimation correctly, pulses received on a local detector must be synchronized with the corresponding one at the remote terminal, i.e., the ith pulse launched from the Earth terminal and received at t_0 by the local detector must be paired with the ith pulse received at t_2 by the remote detector, and the jth pulse launched from the Mars terminal received at t_1 locally must be paired with the jth pulse detected at t_3 at the Earth terminal. This synchronization is a simple process with a common trigger/clock applied to each of the two terminals. However, when the two terminals are far apart and a common trigger/clock is not practical, a synchronization scheme needs to be implemented.

The approach used here to synchronize the two terminals involves launching two different coded sequences of pulses from the two lasers. By comparison with the codes using autocorrelation technique, the origin of each detection event (Earth terminal or Mars terminal) can be identified, along with the position in the sequence (the index i or j of each pulse). Our demonstration used simple repeating coded words; however, more complex codes could be used to increase the ambiguity range. For synchronization and range estimation, the recorded time tags at one terminal need to be transmitted to the other terminal. This can be achieved via free space laser communications or RF communications. The interplanetary laser ranging system could potentially be combined with interplanetary laser communications, and most of the hardware, including the laser, telescope, pointing system, and high-speed detector could be shared between the systems.[9] A communication system would require the addition of a timing system and a timing reference path to enable it to be used for ranging, and a ranging system could perform laser communications by adding modulation capability.

To reduce the random error, the range estimate is computed for each of many pulse pairs, and the estimates are averaged. The random error in the averaged estimate is inversely proportional to the square root of the total number of pulse pairs used for averaging. Using multiple pulse pairs also allow the clocks at each terminal to be compared and any discrepancy to be corrected. For example, a constant frequency difference in the clocks at the two terminals can be corrected by using two consecutive sets of four time tags, namely, $t_0(i)$, $t_2(i)$, $t_1(j)$, $t_3(j)$, $t_0(i+1)$, $t_2(i+1)$, $t_1(j+1)$, $t_3(j+1)$. The correction factor is

$$\alpha = \frac{1}{2}\left[\frac{t_3(j+1) - t_3(j)}{t_1(j+1) - t_1(j)} + \frac{t_0(i+1) - t_0(i)}{t_2(i+1) - t_2(i)}\right] \tag{2}$$

which converts the time differences recorded from terminal B to terminal A by $\Delta t_A = \alpha \Delta t_B$. [12]

3. SYSTEM DESIGN AND EXPERIMENTS

The active laser ranging link can easily be established at the maximum separation between the Earth and Mars of 2.7 AU. Consider, for example, a system using a 1-m ground telescope with a 1-W 1064-nm laser at the Earth terminal and a 15cm diameter telescope with a 0.1-W laser at 1064-nm at the space terminal, and assume transmit and receive optical efficiency to be 0.4, atmospheric transmittance of 0.5 and detector quantum efficiencies of 0.30. Link budget analysis shows that the ground terminal will detect 76 photons/second and the detector at the space terminal will receive 756 photons/second. When applying these example parameters to the longer separation of 6.2 AU (distance to Jupiter), the received count rate is reduced to 14 photons/second at the ground terminal, and 143 photons/second at the Jupiter terminal (following $1/R^2$ scaling).

3.1 Laboratory experiments

To emulate the above scheme for active laser ranging over interplanetary distances, we built two separate terminals using commercial off-the-shelf hardware. A diagram of the laboratory experiment is shown in Fig. 3. Mode-locked lasers with pulse widths of 4 ps at 1064 nm and 5 ps at 1550 nm generated the optical signals. The use of different wavelengths for the two lasers was a matter of convenience and is not necessary for the system. The optical pulses were modulated and coded with FPGA boards (Digilent Inc.). The laser light is collimated and directed to a beam splitter, where some of the light is diverted to a reference arm. The light that passes through the beam-splitter travels to the other terminal through a steering mirror. Photons that arrive at the second terminal are combined with the light from the reference arm via the beamsplitter and focused on to an InGaAs detector. Each terminal was mounted on a translation stage with a micrometer reading. These translation stages were used to vary the separation between the two terminals.

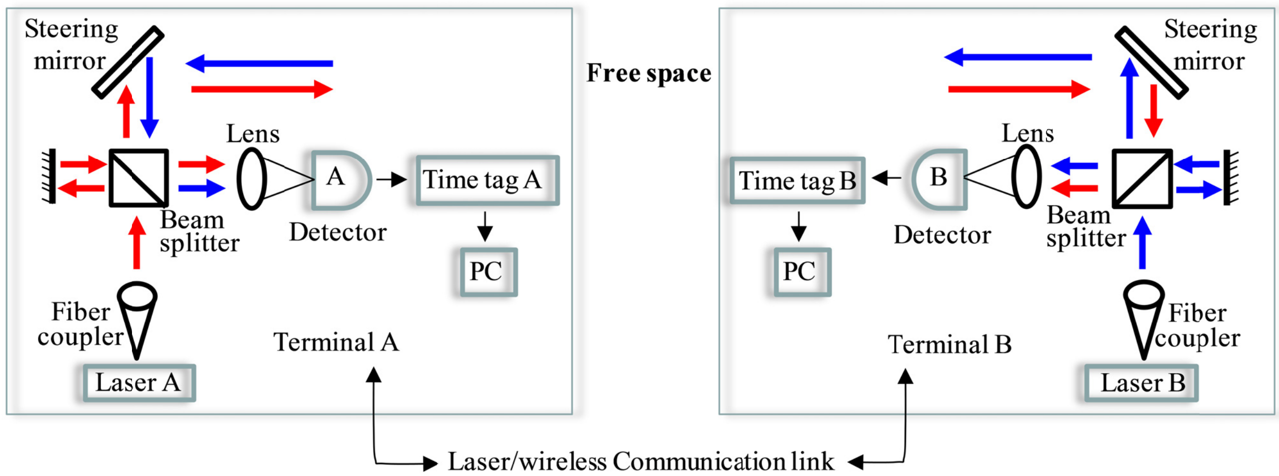


Figure 3. Block diagram of the active laser ranging system used in the laboratory experiments.

Two independent pulses, one from each terminal, resulted in 4 recorded time tags, corresponding to light from Laser A and Laser B, and reaching Detector A and Detector B. The four time-tagged signals were used to compute range according to Equation (1). The calculated ranges were averaged for multiple consecutive pulses to create an average range estimate for a given path length. The correction factor of Equation (2) was included in the data processing to account for the differences in time tag clocks. However, the experiment showed that the correction from the clock difference between the two time tag devices was negligible. The laser repetition rates were set to about 1kHz, which could be reduced to a few Hz for longer ambiguity-range measurements. Adjusting the translation stages with a known amount on the micrometers varied the path length and the measurement procedure was repeated. The distance measured by the ranging system was the length of the optical path between the two reference mirrors, and the changes were well calibrated via the translation stages.

Fig. 4 shows the results of the laboratory experiments. Data was taken and processed in real-time. The communication link for the command to start recording pulse arrival times and data transfer from one terminal to the other was achieved using a standard wireless link, as the implementation of free space laser communication was beyond the scope and budget of the project. Fig. 4a plots the measured range as a function of the path variation from the translation stages. Fig. 4b shows the deviation of the measured ranges from the fit. The deviations are within ±0.14mm peak to valley and the corresponding root-mean-square (RMS) is ±0.039mm. The deviation is well below the goal of 1mm precision. This leaves enough margin to achieve 1 mm precision when including the fluctuations due to atmospheric turbulence while ranging to Mars through the Earth's atmosphere.

The real-time ranging error shown in Fig. 4b includes all the imperfections in the current system, such as detector noise/jitters, laser jitters, and clock error. The results demonstrate that this scheme is robust enough for implementation even with the technology in the currently available commercial hardware, and indicate that this active-ranging scheme is applicable to interplanetary ranging with millimeter accuracy.

Fig. 5 shows pictures of the laboratory setup with the two terminals. Fig. 5a illustrates the two terminals mounted on the translation stages, which can be moved freely on the rail for a wide range of distance with fine adjustment. Fig. 5b describes the terminal constituents corresponding to those in the schematic of Fig. 3. The alignment camera, which facilitates coarse laboratory alignment of the light to the detector, is not shown in Fig. 3.

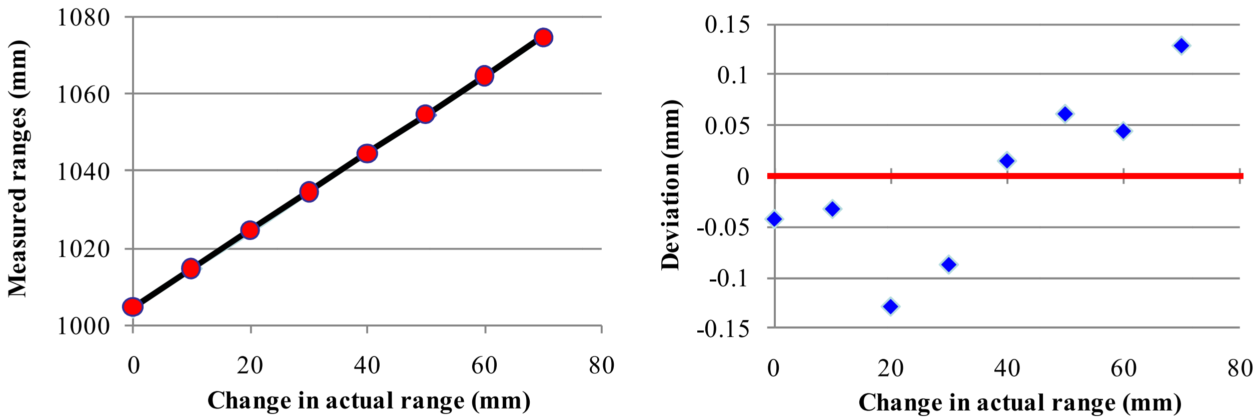
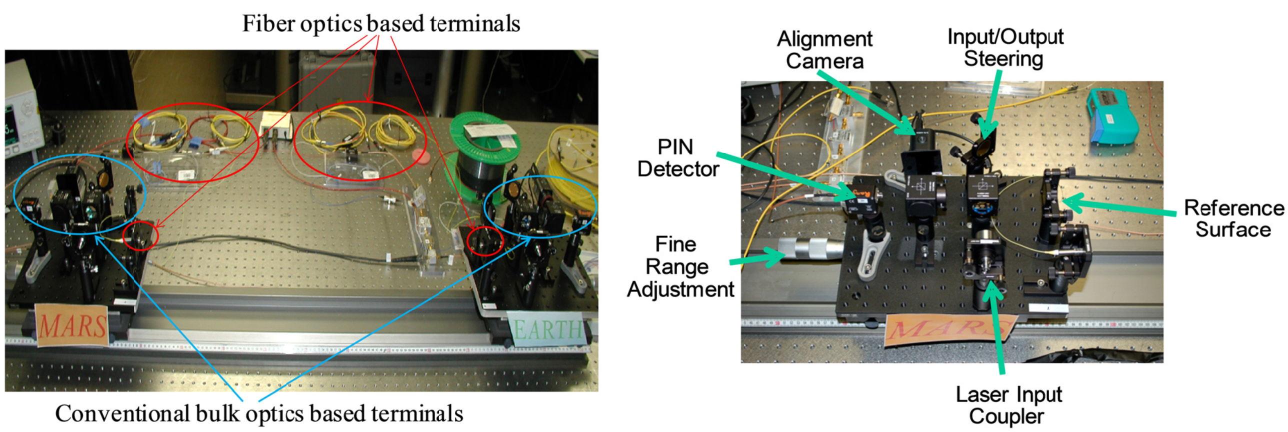


Figure 4. Experimental data from the laboratory demonstrations. (a) Measured range vs. the actual change in range from translation of the terminals. The experimental results are indicated by the filled circles in red. The black curve is a line with a unit slope and an offset chosen to minimize deviation from the data. (b) Deviation of the measurements in (a) from the line. Blue diamonds indicates the experimental results. Each data point represents 1000 sample measurements.



(a) (b)

Figure 5. Pictures of the laboratory setup for active laser ranging.

3.2 Field experiments

In additional to the conventional bulk-optics-based terminals, fiber-optics-based terminals were built for field-testing. A diagram of the setup is shown in Fig. 6. All the optical connections between the elements within the terminals are through fibers. This configuration reduces variables for alignment, but introduces coupling losses between the source and the different fiber components. In this experiment, again we used a 1550nm laser for one terminal and 1064nm for the second terminal. The fiber coupler has 3 dB splitting loss at both wavelengths. InGaAs APDs with appreciable response over a wavelength range of 800-1650nm were used for detectors. Fiber in-line attenuators were used to adjust the reference path signal, making it comparable with that received from the remote terminal.

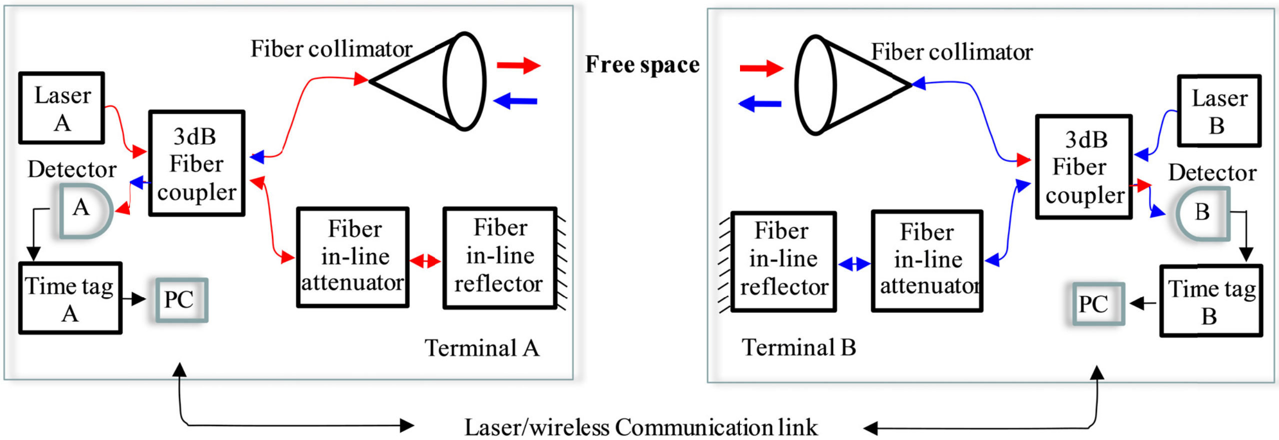


Figure 6. Block diagram of the active laser ranging system used in the field experiments.

Using the fiberoptics-based terminals, we performed field tests of the ranging system. Fiber collimator heads were mounted on translation stages with micrometer readings, and each was placed on a tripod. Fig. 7 is a picture of one terminal with a description of the parts. The two terminals differ only in the wavelength of the mode-locked lasers. They were coarsely aligned with a visible reference laser. Fine-tuning was completed at the operational wavelengths of 1064nm and 1550nm. For further development, automatic alignment needs to be implemented by mounting the fiber collimators on two-axis gimbals, which can be commanded through software locally and remotely. Because of the robust nature of the fiberoptics-based terminals, gimbal movement will not affect internal alignment. Automatic tracking using gimbals will keep the two terminals pointing at each other for continuous ranging measurement as the terminals move.

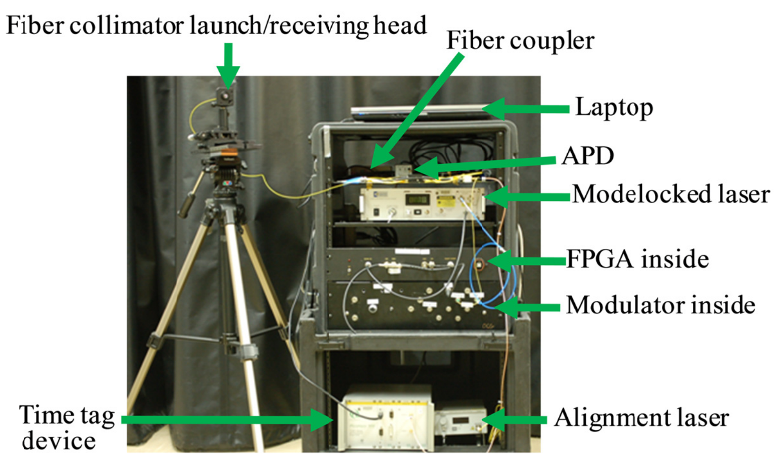


Figure 7. Active laser ranging field equipment.

The results of the field experiments are shown in Fig. 8. The two terminals were separated by approximately 16 meters. The ranging errors were about ±0.16mm peak to valley (with the corresponding RMS of ±0.05mm), similar to those in the laboratory experiment. The sub-millimeter range accuracy as measured in the field is expected to leave sufficient margin to meet the goal of 1-mm range accuracy when including atmospheric-induced turbulence effects (as seen in links between the ground and space). In the field, commands for starting to tag pulse arrival times and time tag data transfer between the two terminals were achieved via wireless communication link. Data processing was done in real time.

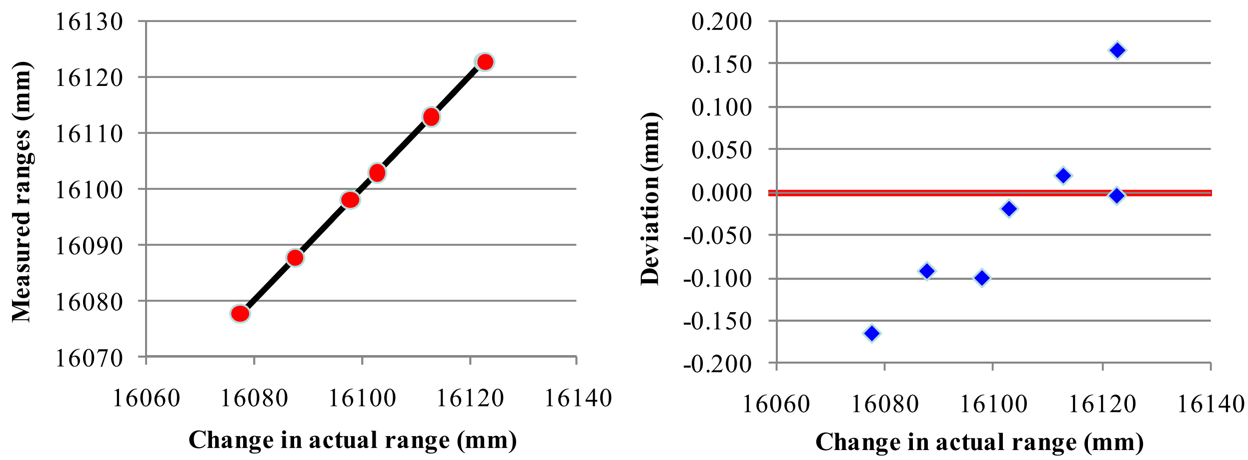


Figure 8. Field experiment results. (a) Measured range versus the change in actual range from translating the terminals. The filled circles in red indicate the experimental results. The black curve is a line with a unit slope and an offset chosen to minimize deviation from the data. (b) Deviation of the estimates in (a) from the line. Blue diamonds indicates the field experimental results. Each data point represents 1000 sample measurements.

4. CONCLUSION

We have demonstrated the real-time active laser ranging using a method applicable to interplanetary distances. Sub-millimeter ranging accuracy has been achieved with the systems built from off-the-shelf commercial components, demonstrating the robustness of the scheme. The experimental results indicate that active laser ranging can be implemented for interplanetary distances to meet the goal of 1mm ranging accuracy, including the effects of the Earth's atmosphere. This paves the way for advances in the study of fundamental physics and solar system dynamics.

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